" Dynamic Models of Earthquakes, Fault Systems, and Earthquakes on Fault Systems "

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Program Element I

Investigations undertaken

Earthquakes are complex in many ways. The slip in an individual event, the distribution of sizes of events, when they occur, and where they occur, are just some of the complexities we would like to understand. A fundamental, open question, is what is the source of the complexity. Recent work on simple models has shown that a remarkable degree of complexity can be generated by the self-organization of repeated ruptures on a fault. A particularly interesting class of models are deterministic, elastodynamic models in which all the complexity is generated by a frictional instability. Here, distributions of interesting quantities are produced, without any distributions of any quantities having to be assumed. It is important to ask how the behavior of these models compares with the Earth; how well do these simple models agree with what is seen in the Earth, and in what ways do they need to be made more complicated to agree better? What insights can they give us about what might be happening in real earthquakes?

The program of research involves the development and characterization of elastodynamic models which produce complex sequences of events from a frictional instability. There are two basic goals in this research. One is to develop models of earthquake faults that produce realistic behavior across the whole range of timescales in the earthquake cycle, from the fast rupture timescale to the slow loading cycle. The second goal is to develop better ways of quantifying the complex behavior that is seen in the models; this helps us to better understand what is happening in the models, to compare the behavior produced by different models, and, most importantly, to compare with the behavior seen in the Earth, and, perhaps, to suggest new ways of looking at the data from the Earth.

The main new thrust of research carried out with support from this grant was the examination of a new class of behaviors which occurs in the new higher dimensional elastodynamic models: wave energy radiated from motions on the fault. This radiated energy is particularly important for two fundamental reasons. First, nearly all the damage in earthquakes is caused by the shaking, and improving our understanding of these waves can help in efforts to minimize damage from them. Second, the greatest amount of earthquake observational data resides in seismograms, and being able to compare models against those observations will ultimately provide the strongest constraints and tests of the models.

Results

The simplified elastodynamic model used in the study of radiated energy consists of a long strip of scalar elastic bulk (mode III), the wave equation, bounded by a fault boundary on one side, and a constant velocity boundary, meant to represent the stable sliding at depth, on the other. When the friction weakens with either slip or slip rate, a complex sequence of events develops. The geometry of the model is illustrated in Figure 1.

Motions on the fault cause motions in the bulk. In the near field, much of the kinetic energy goes to rearranging the displacement field, and thereby goes into rearranging the potential energy density. Only some of the kinetic energy manages to escape to the far field, and is radiated away. One way to visualize the near field motions is with an array of velocity records. Taking an array of records located near but off the fault, and spaced evenly along the fault, as indicated in Figure 1, we can observe the coherent motions created by an event. Figure 2 shows two events, one small, in Figure 2a, and one large, in Figure 2b. The small event illustrates a sort of "empirical Greens function" for the medium. The horizontal axis is time, and the vertical axis is velocity, with neighboring velocity records offset vertically by a constant amount. We see an initial short velocity pulse, corresponding to the short event, followed later by a broad reflection of the waves scattering off of the stiff slowly moving boundary a distance unity from the fault. A large event is shown in Figure 2b, with a decreased magnification of the time and velocity axes. We see the relatively messy epicentral region organizing into two large pulses of slip emanating bilaterally down the fault. Coherent packets of scattered energy ring on behind the passage of the main rupture pulse. This visualization provides a qualitative picture of some of the complex spatial and temporal aspects of the radiative field in the bulk. To provide a more quantitative measure of the behavior, we step back to the far field

One could measure, directly, the far field radiated energy by integrating the energy flux through a far surface which enclosed the source. One would, however, have to wait a long time for the waves to travel to the far surface, and for all the scattered waves to finish passing through it. I circumvent this difficulty by using conservation of energy. I keep track of the work done on the boundaries, and calculate the potential energy change in the static solution before and after the event. Then the difference between the potential energy before and after an event, minus the work done on the boundaries is the radiated energy E, since there are no other energy sources or sinks in the model (for this calculation there is no dissipation in the bulk). This conservation of energy method works because we are solving things in a consistent dynamic– as opposed to kinematic– way.

To check the consistency of the methodology, I have done a number of tests. First, I have checked that the results are independent of the spatial grid resolution and temporal time step resolution. Second, I have tested the method on a reduced one-dimensional model, where the loading boundary is only one grid element away (the model of Burridge and Knopoff [1967]), and measured that indeed, as expected, there is no radiated energy (to the resolution of 10^{-6} of the method). Third, I have checked that the radiated energy is independent of the absolute level of stress, and only depends on the stress drop; changing Φ_0 leaves the results unchanged. Finally, I have checked that in the limit where the friction drops very rapidly with time to a nearly constant value the efficiency goes to unity, as expected.

The main results are shown in Figure 3. This shows the radiated energy E, as a function of moment M, for different values of the friction parameter γ going from slip-weakening at small γ to velocity-weakening at large γ. Each point corresponds to an individual event, with the different symbols representing different values of γ. There are a number of things that can be seen in the figure. First, larger values of γ, more velocity weakening, gives more E for a given M. Slip-weakening, small values of γ, gives very little radiation, and a nonlinear scaling of E with M. Neither of these features for the slip-weakening case appears to be realistic when compared to the observations. In contrast, velocity-weakening gives both a linear scaling of E with M, and values of η which, while small, are consistent with observations.

Small seismic efficiencies have been puzzled over by researchers for a long time [e.g. Kanamori, 1994]. Here, I have shown that they can arise naturally in the context of elastodynamics with friction. For the frictions studied here, slip-weakening was seen to be inconsistent with observations, having a nonlinear radiated energy-moment scaling and too-small seismic efficiencies, while velocity-weakening was seen to be consistent, having a linear radiated energy-moment scaling and small but reasonable efficiencies. Much discussion in self-organizing models has focussed on the question of what the distribution of sizes of events is. Independent of that issue, however, is the very important question of what the events themselves look like. In this research, I have examined, qualitatively, coherent near-field velocities, and, quantitatively, far-field radiated energies. This work opens up new axes of comparison of elastodynamic models with observations, where there is potentially a vast amount of observational constraints, and with potentially great practical uses.

Nontechnical summary

This research aims to understand what the basic physics of earthquakes is. What is happening at the source? Can we write down mathematical equations that behave in ways that are similar to earthquakes? In addition to developing better models of the earthquake process, we seek to develop better ways of quantifying the complex behavior that is seen in the models. This helps us to better understand what is happening in the models, to compare the behavior produced by different models, and, most importantly, to compare with the behavior of seen in the Earth, and, perhaps, to suggest new ways of looking at the data from the Earth.

Reports Published

Bruce E. Shaw,
'Modelquakes in the Two-Dimensional Wave Equation',
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Bruce E. Shaw,
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